Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness

Ran Fu, Ted L. James, and Michael Woodhouse

***Abstract*—Several economic metrics are presented for polysilicon in the solar photovoltaics (PV) industry. The overall level of market competition through exploration of the Herfindahl–Hirschman index and consolidation for the current polysilicon industry is quantified. In addition, for several international manufacturing locations, the most recent results in bottoms-up manufacturing cost and price modeling are shown for Siemens hydrochlorination (solar-grade), Siemens hyperpure, and fluidized bed reactor production of polysilicon. Finally, the entry barrier, which is defined as the upfront capital requirements to become a competitively sized facility, is quantified for today's polysilicon industry.**

***Index Terms*—Industrial economics, manufacturing competitiveness, photovoltaics, polysilicon cost and price.**

I. Introduction

THIS paper uses the calculations of several economic indicators to quantitatively measure the market competition, manufacturing costs and prices for different technologies in different facility locations, and capital cost requirements to enter today's polysilicon market. The scope of this analysis is limited to the global polysilicon industry as the first step of the crystalline silicon photovoltaic (PV) value chain analysis (see Fig. 1).

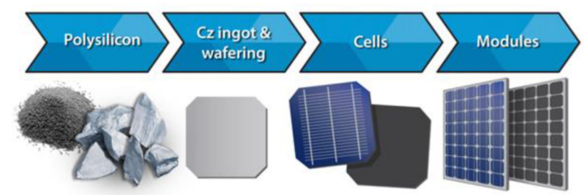

Fig. 1. Wafer-based monocrystalline silicon PV manufacturing supply chain [1].

Historically, polysilicon was the main material for integrated circuits in the semiconductor industry. Before 2000, more than 80% of polysilicon was consumed by the semiconductor industry, but over a decade, the picture of polysilicon demand has been evolving; now, it is mostly used for manufacturing PV cells [2]. During 2008–2014, 60–80% of polysilicon was consumed by the solar industry [3]. This demand transformation within the polysilicon industry leads the market price of polysilicon to experience dramatic fluctuations during the period of ∼2004–2014: first undersupply (when the average selling price approached US$ 400/kg in 2008) and then oversupply (when the average selling price dropped to less than US$ 20/kg in 2012) [4]. Since polysilicon is the feedstock for PV manufacturing and its price is the starting point of the entire silicon PV supply chain, downstream producers of wafers, cells, and modules have had to deal with these price fluctuations, and the effects on manufacturing costs have been significant. Since 2008, polysilicon price decreases have contributed about US$ 2.3 per Watt to the decline in total module production cost.[1]

In addition to supply–demand imbalances, polysilicon price variations are also due to manufacturing cost differences. These technology choices include Siemens with hydrochlorination, Siemens with direct chlorination, Siemens with silane, fluidized bed reactor, upgraded metallurgical grade, and vapor to liquid deposition. Each technology will produce different purities of polysilicon from 5N (five nines, 99.999%) to 10N for solar-grade, or, even purer, 11N+ for electronic-grade. In addition, different facility locations have different electricity rates, labor rates, raw material costs, and capital expenditures (CapEx), which can also significantly influence manufacturing costs.

To describe the current polysilicon market, one should assess the market competition, the drivers of manufacturing costs and prices for different technologies and facility locations, and the capital cost requirements for a new investor to enter this market today.

Primary economic metrics—the Herfindahl–Hirschman index (HHI), the weighted average cost of capital (WACC), "all-in" production cost, the minimum sustainable price (MSP), and the entry barrier in terms of capital cost requirements—are analyzed in this paper to address these important questions within the context of global polysilicon manufacturing.

II. Market Competition Measurement

Over the past ten years, about 60 to 80 [6] emerging small- and medium-scale producers have entered the global polysilicon market. The result has been a dramatic shift to recent severe overcapacity and overproduction of polysilicon and dramatic declines in the market price. Fig. 2, for example, demonstrates

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The authors are with the Strategic Energy Analysis Center, National Renewable Energy Laboratory, Golden, CO 80401 USA (e-mail: Ran.Fu@nrel.gov; Ted.James@nrel.gov; Michael.Woodhouse@nrel.gov).

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[1]Polysilicon price of US$ 400/kg in 2008 × Assumed silicon utilization of 6.0 g/W in 2008 = Polysilicon price in the module US$ 2.40/W in 2008; Polysilicon price of US$ 23/kg in 2014 × Current silicon utilization of 5.3 g/W in 2014 [5] = Polysilicon price in the module $0.12/Watt in 2014.

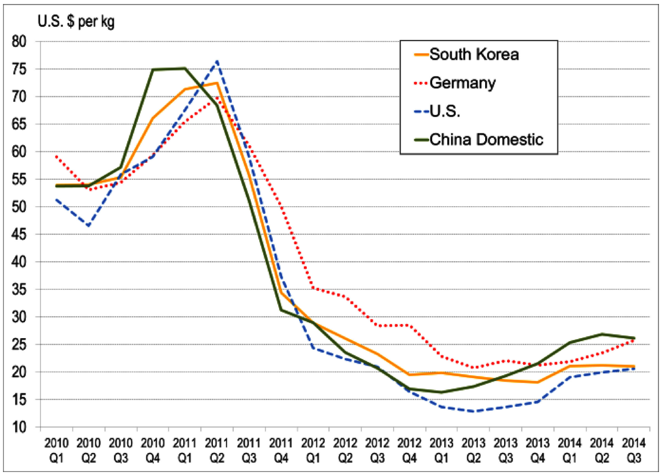

Fig. 2. Historical imported and domestic polysilicon price in China, compiled from General Administration of Customs of the People's Republic of China. The imported price is defined as cost, insurance, and freight [7], [8].

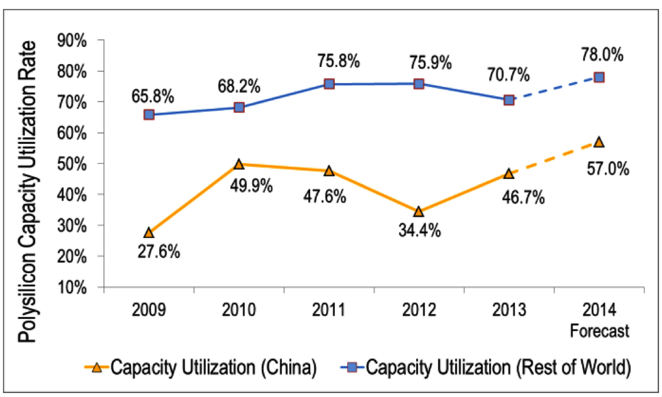

Fig. 3. Global polysilicon capacity utilization ~2009–2014 [6], [10].

the historical quarterly imported and domestic polysilicon prices (mix of spot price and contract price) in China, which is currently the largest consumer of solar-grade polysilicon in the world.

Improvements in polysilicon manufacturing technology and plant economies of scale have significantly reduced the manufacturing costs [9]. Increased polysilicon plant scaling has become a common trend, especially in China. At the same time, high capacity is not necessarily correlated with high utilization, based on observations of capacity versus production. Figs. 3 and 4 show that Chinese producers, compared with other producers, have had the lowest utilization rates globally.

A universal index that can be employed as an indicator of market competition and consolidation is the HHI, which is defined as the sum of the squares of the market shares of each firm in the industry. The greater weights are given to the firms with higher market shares. The inverse of the HHI calculates the number of effective competitors (NEC) who will have pricing power as the producer [11]. Mathematically, HHI is denoted as [12]

$$\text{Herfindah–Hirschman Index} = (S_1)^2 + (S_1)^2 + \ldots (S_n)^2 \quad (1)$$

where S_i is the market share of firm i in the market.

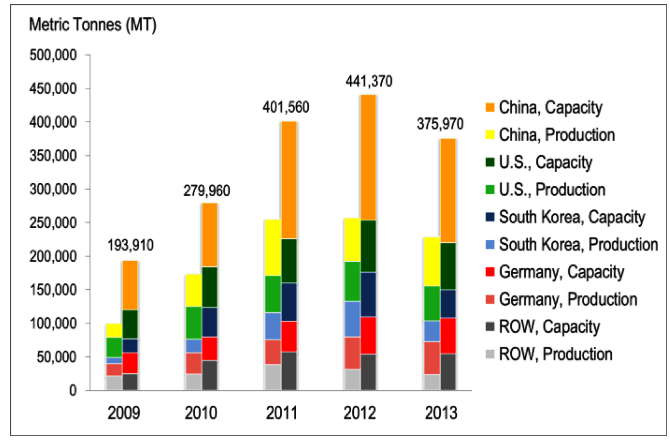

Fig. 4. Global polysilicon production and capacity ~2009–2013 [6], [10].

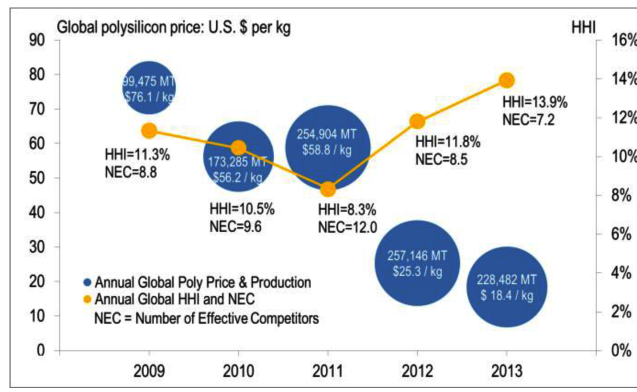

Fig. 5. Global HHI and NEC of polysilicon industry ~2009–2013 [6].

The function of the HHI measurement has been emphasized in the U.S. merger and antitrust guidelines. Based on the range of HHI values, the U.S. Department of Justice and the Federal Trade Commission have defined four categories [13].

$0 < \text{HHI} < 1\%$	A highly competitive market
$1\% < \text{HHI} < 15\%$	An unconcentrated market
$15\% < \text{HHI} < 25\%$	A moderately concentrated market
$25\% < \text{HHI} < 100\%$	A highly concentrated market

Fig. 5 illustrates the calculation of HHI and NEC for the global polysilicon industry. It indicates a fluctuation in market concentration from 2009 to 2013. In 2013, the global HHI was calculated as 13.9%, which was defined as an unconcentrated market, and the NEC declined to be 7.2, suggesting that more and more producers are exiting the market. Notwithstanding that 2013 annual global polysilicon production (size of blue bubble) was still large and global polysilicon price was still low, the actual turning point occurred in 2011. Before 2011, market competition increased sharply, with hundreds of new entrants, most of whom were Chinese solar-grade polysilicon producers. After 2011, the market became less competitive (or more concentrated) in terms of higher HHI and lower NEC. This trend implies that the ongoing industry consolidation has been gradually taking place since 2011 and the overcapacity structure has been mitigated with fewer but larger manufacturers. This may also explain the price rebound in 2014 Q1 shown in Fig. 2 since pricing power is shared by fewer manufacturers (namely, smaller NEC).

III. Calculated Manufacturing Costs and Minimum Sustainable Prices of Polysilicon

Although the market competition analysis indicates the polysilicon industry may be moving toward a more consolidated market and supply–demand equilibrium could be rationalized in the near future, analysis is still needed to understand the potential price equilibrium and manufacturing competitiveness of each technology using the modeled “all-in” production cost and MSP [14].

In spite of the various technologies employed in polysilicon production, the majority of polysilicon used by the semiconductor and solar industries is based on the chemical vapor deposition (CVD) methods for purifying metallurgical grade silicon (MG-Si) from low purity (1 N–2 N, 98.5–99.5%) to much higher purity (> 99.9999%, or 6 N, to 11 N) [10], [15]. First, the MG-Si is typically produced by the carbothermic reduction of quartzite in an arc furnace at very high temperatures (1800–1900 °C) [16].

$$\mathrm{SiO_2} + 2C \rightarrow \mathrm{MG-Si} + 2\mathrm{CO}.$$

The current commercial technologies for the purification of the Si to higher purity levels can include:

1) *Siemens With Hydrochlorination (HC)*: Trichlorosilane (TCS, formula: $\mathrm{HSiCl_3}$) hydrogen, MG-Si, and silicon tetrachloride (STC, formula: $\mathrm{SiCl_4}$) are introduced into the reactor to form TCS at a reaction temperature of 500–550 °C and pressure of 25–33 bar (gauge) according to the reaction [2], [17]

$$2\mathrm{H_2} + \mathrm{MG-Si} + 3\mathrm{SiCl_4} \rightarrow 4\mathrm{HSiCl_3}.$$

2) *Siemens With Direct Chlorination (DC)*: MG-Si and hydrogen chloride (formula: HCl) are contacted at 300–360 °C and pressure of 6 bar (gauge) according to the reaction [18], [19]

$$\mathrm{MG-Si} + 3\mathrm{HCl} \rightarrow \mathrm{HSiCl_3} + \mathrm{H_2}$$

and then $\mathrm{HSiCl_3}$ is purified by the distillation plant and polysilicon is grown by CVD on slim rods

$$\mathrm{HSiCl_3} + \mathrm{H_2} \rightarrow \mathrm{Si} + 3\mathrm{HCl}.$$

Since TCS produced from both HC and DC processes is a mixture of chlorosilanes, further separation and purification is required. Although HC requires more steam for distillation than DC, HC consumes less electricity for every kg of STC converted and has lower upfront CapEx due to fewer unit operations [17]. Both HC and DC processes can produce a purity of 9N and are generally the mainstream technologies today.

3) *Siemens With Silane*: Instead of TCS, monosilane (silane, formula: $\mathrm{SiH_4}$) gas is used as the alternative feedstock for high-purity polysilicon. Silane gas is introduced in the Siemens CVD reactor for the thermal decomposition at a lower temperature, between 370–450 °C [20]. The reaction can be simplified as

$$\mathrm{SiH_4} \rightarrow 2\mathrm{H_2} + \mathrm{Si}.$$

While this process can produce high-purity (9N +) polysilicon, silane is a pyrophoric gas and any leaked silane that comes into contact with air could explosively combust [3].

4) *Fluidized Bed Reactor (FBR) With TCS*: Purified TCS is heated with hydrogen gas and introduced into the FBR CVD furnace to form granular polysilicon. The seed particles will grow as the gas is decomposed on their surfaces. Eventually, $\mathrm{HSiCl_3}$ gases will be recycled in the furnace [3].
5) *FBR With Silane*: Instead of TCS, silane gas is heated and converted in a similar process. The difference is that this process is free of residual $\mathrm{HSiCl_3}$ gases [21].

Compared with the Siemens methods, the FBR method uses less electricity since it is a continuous process and the reactor provides a hot wall, whereas Siemens is a batch-based process with the cold wall design. FBR does, however, require more steam. In comparison to solely utilizing Siemens-produced polysilicon, because the finer granules can fill the voids between the pieces of chunk the inclusion of FBR-produced granular polysilicon in the melting crucible is reported to save 41.2% crucible filling time and increase the crucible charge weight by 29.4% [21], [22]. Therefore, although the FBR method offers relatively lower purity (8N), it is still considered to be an economically compelling material in the downstream wafering step.

6) *Upgrade Metallurgical*: MG-Si is chemically refined in this new process invented for low-cost solar-grade polysilicon. Gases are used to blow through the silicon melt in order to remove the boron and phosphorous impurities [23]. Directional solidification follows. Although the cost reduction of this method is advantageous due to the lower electricity consumption (estimated as 30–40 kWh/kg) compared with the Siemens methods, the purity of produced polysilicon is much lower (5N–6N) than the Siemens process [24].
7) *Vapor to Liquid Deposition*: This method first produces $\mathrm{HSiCl_3}$ by reacting MG-Si with chlorine (formula: $\mathrm{Cl_2}$) and hydrogen, and then $\mathrm{HSiCl_3}$ is purified through distillation and hydrogen reduction process at temperature range of 1350–1500 °C [10]. The deposition of liquid silicon from gas occurs in a graphite tube. It is similar to the Siemens methods in (1) and (2) in using $\mathrm{HSiCl_3}$ gases, but the deposition rate (or extraction speed) is ten times faster than the Siemens process CVD reactor [10]. The purity is claimed to be 9N [25].

Although there are a variety of polysilicon manufacturing technologies, the global production in 2013 was shared by four mainstream methods: Siemens HC (production 108 920 t), Siemens DC (production 79 000 t), FBR with silane (production 20 150 t), and Siemens with silane (production 3620 t). In Fig. 6., the market share of production (%, x-axis) and reported cash costs (US$/kg, y-axis) are marked for selected global polysilicon producers and their various facility locations. For example, Renewable Energy Corporation (REC Solar ASA)

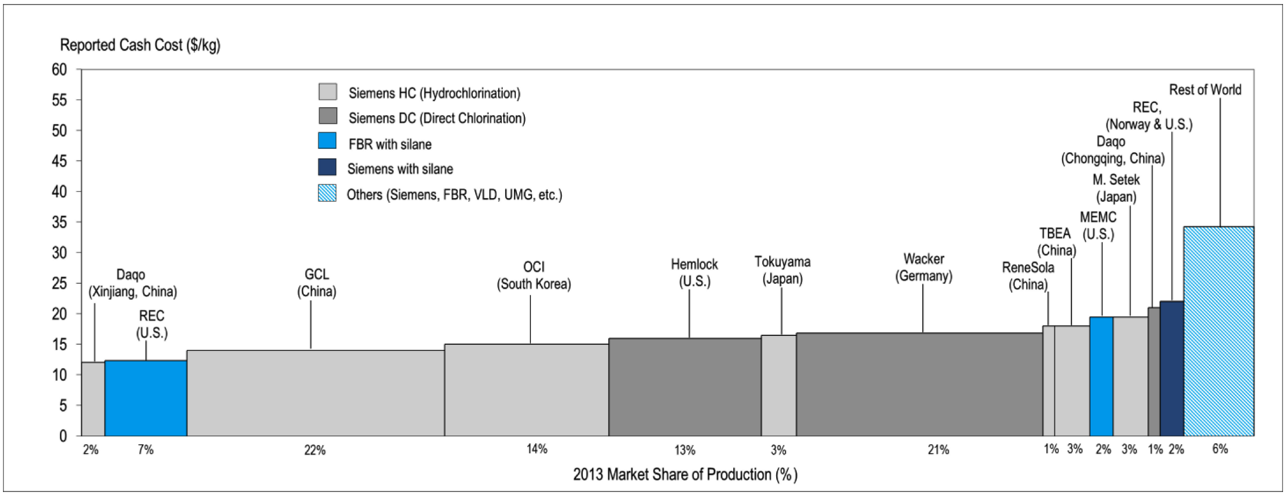

Fig. 6. Supply curve of selected global polysilicon producers (2013).

uses Siemens with silane to produce polysilicon chunk, as well as FBR, in its facilities in the U.S. and Norway, and uses FBR with silane in a different facility in the U.S. In China, Daqo New Energy has two facilities, i.e., one in Chongqing and another one in Xinjiang, to produce polysilicon with Siemens HC. It is clear that most of the facilities with large production capacities also demonstrate relatively lower reported cash costs. This is largely due to the impact of economies of scale in polysilicon manufacturing. The cash cost here is defined as the costs (per unit of output) that manufacturers pay for the direct production activities on-site, including raw materials, electricity, labor, and maintenance costs but excluding depreciation, research and development (R&D), and selling, general and administrative (SG&A) expenses. For accounting purposes, the cash cost can also be commonly referred to as the cost of goods sold (COGS) on the income statement in a company's financial report, and the company's gross margin can be computed by deducting COGS from revenues (or sales). Information used in Fig. 6 is compiled from various sources [3], [6], [10], [21], [22], [25]–[35]. In addition, note that companies have different products in terms of purities; therefore, their reported cash costs are a mixture of products having different purities. The impact of different purities on cost and price is discussed in a later section.

In order to assess the implied cost drivers and compare the manufacturing competitiveness of different technologies and facility locations, the single cash cost definition would not be sufficient. It is necessary to break down the cash cost into finer categories for a higher resolution, and to also add incremental categories, including depreciation, R&D, and SG&A in order to estimate "all-in" production cost. Especially, for the industrial manufacturers, depreciation is considered as a large operating expense due to the high value of fixed assets (e.g., equipment and factory) [36]. For accounting purposes, "all-in" production cost can also be referred as the expenditure that a company incurs for operating the business. Compared with "all-in" production cost, CapEx is the cost of new fixed assets or the value added to the existing fixed assets [37]. In this manufacturing cost model, the depreciation part in "all-in" production cost is calculated using CapEx (equipment, tooling, and building costs) and a ten-year straight-line depreciation schedule.

In the model, the cost comparisons are included as follows:

1) *Siemens HC Versus FBR With Silane*: These two technologies dominated the 2013 production market and are expected to continue this domination in the near future. In addition, FBR with silane is the pioneer leading the cash cost reduction in the industry. The reported lowest cash cost using FBR with silane was US$ 12.3/kg in 2013 and US$ 10.5/kg in Q4 2013 [29]. These comparisons can help to estimate the manufacturing competiveness between the two leading technologies in the current market.
2) *Solar Grade (9N) Polysilicon Versus Hyperpure (9N to 11N Electronic Grade) Polysilicon*: Although the majority of manufacturers have adopted the similar Siemens CVD as the main process, the polysilicon purity outcome could vary based on different facilities. For instance, hyperpure polysilicon is produced for the semiconductor market, and hyperpure polysilicon is reported to help improve cell efficiency [38]. These comparisons can help estimate manufacturing costs of polysilicon for different purities.
3) *U.S. Facility Versus Chinese Facility*: As the two largest polysilicon manufacturing countries, as shown in Fig. 4 (22.7% global production from the U.S. and 31.8% global production from China in 2013), two location scenarios of the U.S. and China are modeled to assess the regional competiveness. Because of different CapEx, raw material costs, electricity rates, and labor rates, the modeled "all-in" production costs vary accordingly. Two cases are analyzed for China: urban and rural regions. This higher resolution can better characterize the breadth of current and future manufacturing costs in China.

Before these three comparisons are demonstrated, some key model input assumptions are listed in Tables I–III.

In Table I , the U.S. labor bare wages for different occupations are established based on a survey from the U.S. Bureau of Labor Statistics [39]. Respectively, bare wage refers to the direct payment for time worked including basic wages, overtime

TABLE I
REGIONAL COMPETITIVENESS MODEL INPUT ASSUMPTIONS (2014)

Region	U.S.		China	
Bare wage	67.1%		65.0%	
Benefit & Insurance	32.9%		35.0%	
	Bare cost	Compensation cost	Bare cost	Compensation cost
Production worker (US$/hour)	13.55	20.19	1.58 (Urban) 0.62 (Rural)	2.43 (Urban) 0.95 (Rural)
Equipment operator (US$/hour)	23.68	35.29	2.77 (Urban) 1.09 (Rural)	4.26 (Urban) 1.68 (Rural)
Industrial Engineer (US$/year)	82,491	122,937	9,641 (Urban) 3,793 (Rural)	14,832 (Urban) 5,835 (Rural)
Electricity rate (Cents /kWh)	Average: 4.5		Urban (e.g. Jiangsu): 11.5 Rural (e.g. Xinjiang): 5.3	
Average effective corporate tax rates	27.7%		21.5%	
Currency: 1 US Dollar (USD) = 6.26 China Yuan (CNY), May 4, 2014				

premiums, and shift; benefit refers to payment for time not worked including holidays and saving funds; and social insurance refers to the employer insurance expenditure and labor taxes including disability pension, health insurance, and unemployment insurance [40], [41].

The survey median (50th percentile) is used as the typical bare wage, and the compound growth rate of U.S. historical customer price index between 1999 and 2013 [42], [43] is used to compute the modeled 2014 wages. In addition to the bare wage, benefit and social insurance are presented as the percent of total compensation costs. Due to the relatively large variety of living expenses across China, labor rates are further defined for urban and rural regions.

U.S. electricity rates, defined as the average retail price of electricity to a customer in the industrial sector, are based upon data from U.S. Energy Information Administration reports [44] and industry collaborators. China's large-scale industrial electricity rates vary depending upon location. Several large Chinese polysilicon facilities are located in eastern urban regions, where regulated electricity comes at relatively higher prices compared with western rural regions in China. For instance, based on the latest regulation in 2012, the Jiangsu Province retail price for the restricted high-electricity consumption industry (including polysilicon) is US$ 11.5 cents [45], which increased more than 30% from US$ 8.7 cents [46] in 2008. This rapid electricity rate increase for China's large-scale industry can be interpreted in the context of environmental challenges and implementation of carbon pricing [47]. Beyond the upward electricity rate trend, the typical electricity rate subsidies in China were largely canceled from the central government and distributed to the local government in 2010 [48], [49] in light of China's economy structure transition in the manufacturing industry. Overall, the current high electricity rates in China could be considered to be one disadvantage for polysilicon manufacturing in that country since it is a highly electricity-intensive process. To address this, some Chinese producers, located in high electricity rate provinces, have relocated their facilities to the western rural regions where the coal resources are abundant, to alleviate the current pressure on increased electricity rates. The strategic advantages of having a new facility in the western rural regions (e.g., Xinjiang Province) include lower costs for both electricity and labor. Reportedly, the electricity rate in Shihezi, Xinjiang, is US$ 0.053 per kWh [50], [51] for large-scale manufacturing investment. Although there are still some uncertainties for the large-scale implementation in rural regions in China, including severe weather conditions, shortage of skilled laborers, and long distance transportation to the major customers in the eastern regions, the rural case is specifically developed in this model to assess the potential cost variety within China.

Another geographic factor that affects business operations is the effective corporate tax rates. Based on research of global tax rates [52], U.S. enterprises are faced with relatively higher tax burdens. The United States is estimated to have the fourth highest effective tax rate (27.7%) and the second highest statutory tax rate among OECD countries during the ∼2006–2009 period. Because capital is highly mobile and will flow into investments offering the highest returns [53], a higher corporate tax burden could be considered as a disadvantage for U.S. domestic producers compared with Chinese domestic producers in terms of global manufacturing competitiveness.

Although the improved gross margin, net income, or earnings before interest, taxes, depreciation, and amortization for the major polysilicon manufacturers in 2014 could serve as a positive indication of companies' operational profitability, for equity and debt investors the cost of capital needs to be adequate to meet required rates of return. The WACC is defined as the opportunity cost that an investor could earn elsewhere on projects with the similar risk and capital structure. WACC is used as the nominal discount rate in the discounted cash flow calculation, which measures the value of an investment by determining the present value of future cash flows generated from continuing operations. Mathematically, WACC is denoted as [54]

$$\text{WACC} = \frac{E}{E+D}(r_e) + \frac{D}{E+D}(r_d)\,(1-T) \tag{2}$$

where E is the market value of equity, D is the market value of debt, r_{e} is the cost of equity, r_{d} is the pretax cost of debt, and T is the effective corporate tax rate.

The capital structure is defined as the total equity (E) and debt (D) raised by a company to finance overall operations and growth. In the model, the total equity is computed based on the market capitalization (number of common shares outstanding × share price), and for the total debt, the book value of debt is used to practically estimate the market value of debt since very few polysilicon companies have their debt (in the form of corporate bonds) traded on the market. Note that since the costs of equity and debt should be calculated at the same time, both of them are calculated as of 1/1/2014. Finally, using the estimated WACC as the nominal discount rate, MSP is calculated as the breakeven price which would generate sufficient operating cash flow in the future to cover the upfront capital investment [1], [14].

The process of estimating WACC is described as follows: Unlevered beta (asset beta) can be interpreted as a measure of business risk without using debt, and levered beta (equity beta or stock beta, a measure of the volatility of a stock compared with the whole market) includes debt benefits—that cost of debt financing is typically lower than the cost of equity financing and thus debt could be used for tax shelter [55]. Levered betas of selected manufacturers in each country are first computed using regression analysis of individual stock return and market index return. Then, each levered beta is unlevered to eliminate the benefits of adding debt to the company's capital structure. Average of unlevered betas in each country is used to represent the regional unlevered beta. To estimate the regional levered beta, the regional unlevered beta is relevered again using the industry's debt-to-equity ratios in the U.S. and China, respectively. The unlever and relever equations are denoted as [54]

$$\text{Unlevered Beta, } \beta_U = \beta_E[1 + (1 - T)(D/E)]^{-1} \quad (3)$$

$$\text{Relevered Beta, } \beta_E^* = \beta_U[1 + (1 - T)(D^*/E^*)] \quad (4)$$

where β_{E} is the individual company's equity beta, *D/E* is the individual company's debt-to-equity ratio, and D^*/E^* is the industry's debt-to-equity ratio.

Then, the cost of equity for public companies in the U.S. market is estimated using the capital asset pricing model assuming all investors have the same expectations of security returns [56].

$$\text{Cost of equity, } r_e = r_{f,\mathrm{U.S.}} + \beta_E^*(r_{m,\mathrm{U.S.}} - r_{f,\mathrm{U.S.}}) \quad (5)$$

where $r_{f,\mathrm{U.S.}}$ is the U.S. risk-free rate, and $r_{m,\mathrm{U.S.}}$ is the U.S. market total return (compound annual growth of S&P 500 index and its dividends during $1970 \sim 2013 = 10.40\%$).

Finally, the pretax cost of debt can be computed as the sum of country risk-free rate and the corporate spread based on the reported or estimated corporate bond credit rating. The equations are denoted as [57], [58], [59], [60]

$$\text{Country risk - free rate, } r_f = r_G - r_D \quad (6)$$

$$\text{Pretax cost of debt, } r_d = r_f + S \quad (7)$$

where r_G is the government's ten-year bond yield curve rate, r_D is the sovereign default spread (or country default risk), and S is the corporate spread (or company default risk).

In Table II, the estimated regional cost of equity and regional relevered beta for Chinese manufacturers (21% and 2.4) are higher than U.S. manufacturers (17% and 1.9) since stocks of Chinese companies tend to be more volatile than the comparable U.S. companies within the same market. This then leads equity investors to require a higher rate of return on equity for Chinese companies since their stocks are considered to be more risky. In addition, it shows that the estimated theoretical cost of debt in China (6.5%) is more expensive than in the U.S. (4.2%). This is because on the one hand, sovereign default spread (country default risk) is higher for China, and on the other hand, Chinese companies usually have lower credit ratings because of higher corporate debt levels so that China's corporate spread (company default risk, 2.6%) is higher as well. Therefore, the estimated theoretical cost of debt in China is higher, but in spite of these expectations, reportedly, several loan programs subsidized by local government financing platforms have led to lower overall interest rates in China [61].

TABLE II
REPRESENTATIVE INPUT ASSUMPTIONS FOR REGIONAL WACC FOR POLYSILICON INDUSTRY (1/1/2014)

	U.S.	China
Average regional unlevered beta, β_{U}	1.6	1.4
Industry's debt-to-equity ratio, D^*/E^*	0.22	0.98
Regional relevered beta, β_E^*	1.9	2.4
Estimated cost of equity, r_{e}	17%	21%
Government bond yield curve rate, r_{G}	2.96%	4.71%
Sovereign default spread (bp, basic point), r_{D}	29 bp	84 bp
Estimated country risk-free rate, r_{f}	2.7%	3.9%
Estimated corporate spread, *S*	1.5%	2.6%
Estimated cost of debt (pretax), r_{d}	4.2%	6.5%
Average effective corporate tax rates, *T*	27.7%	21.5%
Estimated regional WACC	15%	13%

Although the calculated cost of equity and the cost of debt for Chinese manufacturers are more expensive than U.S. manufacturers, the calculated regional WACC for Chinese manufacturers is actually lower, as shown in Table II. This is because Chinese manufacturers are often more leveraged: they generally utilize more debt financing from bank loans or corporate bonds rather than using as much equity financing from primary market, in comparison to U.S. manufacturers. Thus, the regional WACC in China is estimated as 13%, which is lower than the estimated regional WACC of 15% in the U.S. This means that if "all-in" production costs are the same for U.S.- and China-based companies, the estimated MSP (or the breakeven price) of polysilicon would be higher for U.S. manufacturers since a higher WACC represents a higher discount rate for the cash flow calculation. However, despite Chinese polysilicon manufacturers currently having a lower WACC than their U.S. counterparts, this trend may change in the future. Local government financing platforms in China for large corporate debts could be risky if the expansion is too rapid [62], [63]. Therefore, it is very challenging for Chinese manufacturers to maintain this highly leveraged business model in the long run, considering that nonfinancial corporate debt in China reached US$ 14.2 trillion at the end of 2013, having surpassed the U.S., becoming the largest issuer of corporate debt in the world [64]. Hence, corporate credit risk (or default risk) is a potential concern for those highly leveraged Chinese manufacturers, as evidenced by the first domestic corporate bond default for a Chinese solar module manufacturer in 2014 [65].

To represent the latest industry trends, the listed model inputs in Table III assume best-in-class scenarios. Currently, China does not have Siemens hyperpure or FBR with silane plants; therefore, the input assumptions for these two technologies are denoted as "if China," and we assume that electricity consumptions would be the same as U.S. facilities.

Labor productivity is computed based on the ratio of total nameplate capacity (metric ton) and total employees. It indicates that although U.S. labor rates are much higher than in China,

TABLE III
BEST-IN-CLASS SCENARIOS FOR TECHNOLOGY, MODEL INPUT ASSUMPTIONS (2014)

Technologies	Siemens HC, solar grade	Siemens, hyperpure	FBR with silane, solar grade
Purity	9 N	9 N–11 N	8 N
Electricity	65 (U.S.)	65 (U.S.)	15 (U.S.)
consumption (kWh/kg)	65 (China)	65 (if China)	15 (if China)
Labor productivity	15 (U.S.)	15 (U.S.)	15 (U.S.)
(MT/employee)	4 (China)	4 (if China)	4 (if China)
CapEx per kg of annual	70 (U.S)	100 (U.S.)	100 (U.S.)
installed capacity ($/kg)	45 (China)	75 (if China)	75 (if China)
Depreciation period (Years)	10	10	10
Maintenance, average percentage of CapEx	5%	5%	5%
R&D + SG&A, average percentage of revenues	10%	10%	10%

comparable Chinese facilities typically hire more employees and thus have lower labor productivity in terms of metric ton per labor. Therefore, the high labor productivity in U.S. facilities can help offset cost disadvantages from its high labor rates.

As for the upfront CapEx, inputs are assumed based on reported data and estimates [1], [3], [10], [21]. The depreciation expenses of facility and equipment are calculated based on specific CapEx. Although accelerated depreciation methods (for example, double declining balance depreciation or modified accelerated cost recovery system) may be used in the actual financial accounting to leverage the tax savings and gain more current after-tax cash flow sooner than later [66], a ten-year straight-line schedule [67] is used in this model to compute the average deprecation for each year. In addition, zero book value and zero market value are assumed by the end of the useful life period; thus, there would be no salvage value for the fixed assets. In reality, different companies may have different preferences for depreciation schedules and other accounting methods.

The final modeled "all-in" production costs and MSP for a best-in-class 20 000-t nameplate capacity polysilicon facility based on different technologies and locations are represented in Fig. 7.

The bars in Fig. 7 represent "costs." After applying the costs of raw materials, electricity, labor, maintenance, depreciation, and R&D plus SG&A, the bottom-up cost model estimates "all-in" production costs for different technologies across different regions. The primary findings for "costs" are as follows.

1.1) *Siemens HC Versus FBR With Silane, for Example, Case ① Versus Case ⑦ in* Fig. 7: In spite of lower electricity cost (in the green color) for FBR than for the Siemens process, the depreciation expense (in the red color) for FBR is actually higher than the Siemens process. In other words, although the modeled cash cost (= raw material + electricity + labor + maintenance) of FBR is the lowest in Fig. 7, if an "all-in" production cost is considered, the cost advantage of FBR due to its low electricity consumption would be offset, to some extent, by its high CapEx (or high depreciation).

1.2) *Solar Grade (9N) Polysilicon Versus Hyperpure (9N to 11N Electronic Grade) Polysilicon, for Example, Case ① Versus Case ④ in Fig. 7*: The higher "all-in" production cost of hyperpure Siemens process primarily results from its higher CapEx. Nevertheless, if a higher purity (9N+) of polysilicon is preferred for the cell manufacturing, this price premium could be accepted by buyers.

1.3) *U.S. Facility Versus Chinese Facility*: Since the Siemens process is highly electricity-intensive, the electricity rate advantage of U.S. facility in case ① is more prominent than the labor cost (in the orange color) disadvantage compared with urban Chinese facility in case ②. Thus, although a U.S. facility will generally be expected to have a higher CapEx (subsequently, a higher annual depreciation) for new facility construction work due to more expensive building materials and construction labors, the overall "all-in" production cost for the U.S. facility and urban Chinese facility are close (modeled cost US$ 25/kg in the U.S. versus modeled cost US$ 23/kg in urban China). However, lower electricity cost and lower labor cost (even lower than urban China) in rural regions may create a lowest cost scenario in China in case ③, which could increase the cost difference of polysilicon between U.S. and Chinese facilities (modeled cost US$ 25/kg in the U.S. versus modeled cost US$ 18/kg in rural China).

Second, the blue dots in Fig. 7 represent "prices," which are defined as the MSP in the previous section. The primary findings for "prices" are as follows.

2.1) *Siemens HC Versus FBR With Silane, for Example, Case ① Versus Case ⑦ in Fig. 7*: Although the modeled "all-in" production cost in the U.S. for FBR with silane is lower than Siemens HC (modeled cost US$ 23/kg for FBR versus modeled cost US$ 25/kg for Siemens), the modeled MSP for FBR with silane is actually higher than for Siemens HC (modeled price US$ 36/kg for FBR versus modeled price US$ 33/kg for Siemens). This is because FBR has higher CapEx so that it could require higher selling price or gross margin to cover its larger interest expense due to the higher debt financing in the capture structure. This means not only cost advantage of FBR may be offset by its high CapEx, but in addition, the modeled MSP could be increased by its high CapEx.

2.2) *U.S. Facility Versus Chinese Facility, for Example, Case ① Versus Case ② in Fig. 7*: Although the difference of "all-in" production costs between the U.S. and China is not significant, i.e., approximately US$ 2/kg, as discussed in previous section, the lower calculated regional WACC used for China would increase the modeled price difference to US$ 5/kg (modeled price US$ 33/kg in the U.S. versus modeled price US$ 28/kg in China). This means currently Chinese manufacturers could potentially benefit from their highly leveraged capital structure and, subsequently, have more price room to compete internationally. However, again, high corporate debt level (or high leverage ratio) for a company would increase its cost of equity since equity investors are risk-averse, and eventually would increase WACC due to the costs of financial distress, including bankruptcy cost, based on static tradeoff theory [55], [68].

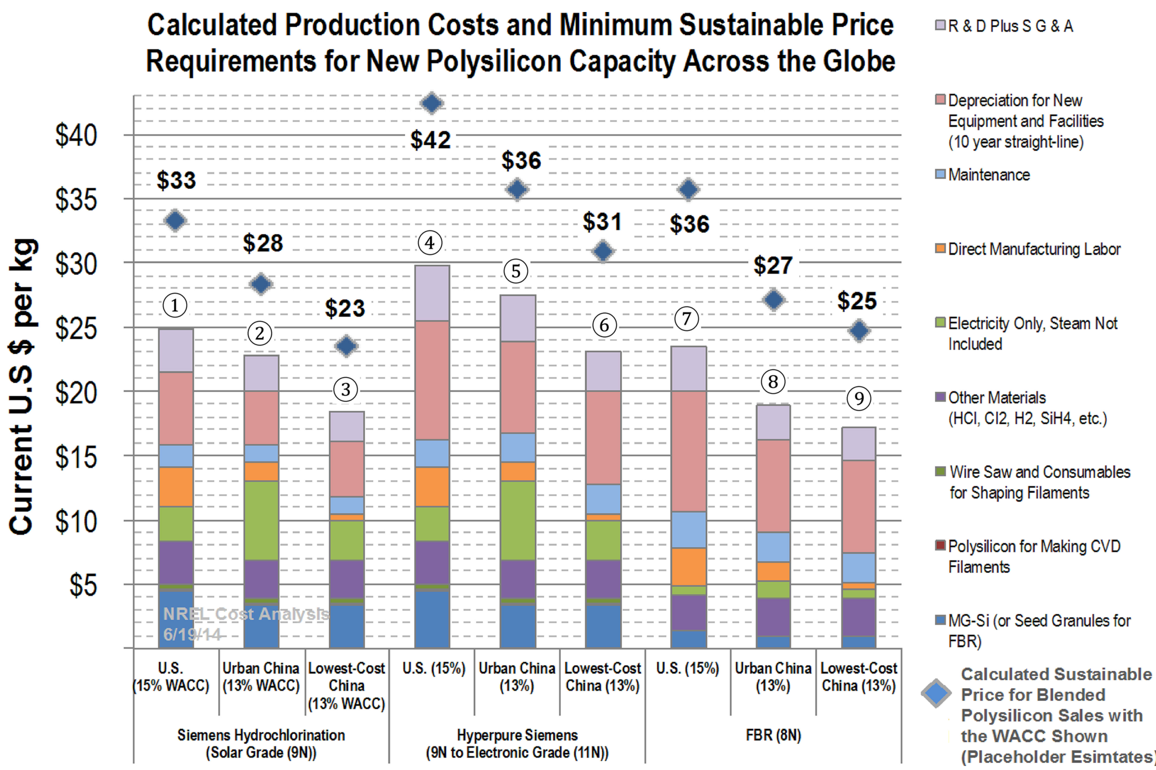

Fig. 7. Calculated "all-in" production costs and MSP for best-in-class polysilicon facilities in 2014.

Third, although competition analysis using HHI and NEC in Fig. 5 shows that today's polysilicon market is consolidating and recovering from overcapacity, the current spot price range in 1H 2014 (US$ 18.72–22.15/kg [69]) is still below the majority of the modeled "all-in" production costs and MSPs in Fig. 7, and thus financially cannot support the rate of return required by investors. Overall, the polysilicon industry is in the slow recovery period considering the current relatively low spot price range. Notably, since long-term contract prices are sometimes higher than market spot price (especially during 2012–2014 when the spot price has been low), some producers with contract agreements may not be limited to this spot price range.

IV. Entry Barriers for Current Market Competition

Irrespective of the technology, each potential new or existing polysilicon manufacturer must ask another question: What would be the minimum scale or capital investment needed to gain pricing power as a producer in today's global polysilicon market? The entry barrier here can be defined as the minimum upfront capital cost requirements to be an "effective competitor"—the next marginal producer, or the (N + 1) competitor as a new entrant in the polysilicon manufacturing business. This metric can help identify the prospect of a potential new investment opportunity in today's polysilicon market. Alternatively, this metric can also approximate the scale or capital level that an existing manufacturer would need to achieve. If this scale or capital level was not achieved, pricing power of a manufacturer would weaken compared with other effective competitors (the NEC calculated in Fig. 5); that manufacturer would eventually face polysilicon price fluctuations [70], as seen in polysilicon history. In Table IV , the entry barrier is qualified for different technologies and facility locations using the CapEx and NEC in today's technology and market competition level. For instance, the capital cost requirement to be the next "effective competitor" for manufacturing Siemens HC solar grade polysilicon in the U.S. is estimated as

TABLE IV
Entry Barriers to be the Next "Effective Competitor" (2014)

Technologies	Siemens HC, solar grade	Siemens, Hyper pure	FBR with silane, solar grade
Number of effective competitors (NEC)	7		
Minimum capacity requirement (MT)	6,500		
CapEx per kg of annual installed capacity ($/kg)	70 (U.S) 45 (China)	100 (U.S.) 75 (if China)	100 (U.S.) 75 (if China)
Capital cost requirements ($ million)	455 (U.S.) 292 (China)	650 (U.S.) 488 (if China)	650 (U.S.) 488 (if China)

$$\text{Production Capacity (MT)} \times \text{CapEx } (\$/\text{kg}) \times (10^3 \text{ kg/ MT})$$
$$= 6500 \text{ MT} \times \$70/\text{kg} \times 10^3 \text{ kg/ MT}$$
$$= \$455 \text{ Million.}$$

The calculated entry barriers in Table IV indicate that because of the shakeout phase and consolidation during the past several years, the current polysilicon market has accumulatively established high requirements for scale and capital investment levels, which could deter new competitors from entering this market, as well as force the existing weaker competitors, who have limited capital sources, to further exit the market in the future.

Another key finding from Table IV is that although FBR with silane has the lowest cash cost, its relatively higher CapEx would be an obstacle for the project financing in the U.S. A potential solution for implementing this high CapEx technology is to seek external partners to share the upfront capital cost requirement for the new manufacturing facilities. Recently, some manufacturers using FBR method had conversations with Chinese partners to discuss the possibilities of setting up joint venture FBR facilities in China [21], [71]. Those dialogues could be explained by the fact that leveraging the lower CapEx in another region (e.g., China) is a feasible solution for financing the technologies with high CapEx requirement (or low bankability). Having access to capital is a vital problem in the silicon PV supply chain, especially for the current polysilicon industry, which has high barriers to enter. In the context of the manufacturing CapEx challenges, international collaborations to broaden the financing channels could facilitate technology implementation and capacity expansion. Nevertheless, there is concern among the international polysilicon investors in China, regarding the risk of leaking their "know-how" of the process experience to the Chinese partners or competitors.

Besides capital cost requirements, other factors including government policy access to distribution channels, and customer switching costs can also be considered as entry barriers [72].

V. Summary of Results

Economic measurements of the polysilicon industry are provided in terms of both market competition and manufacturing competitiveness. The increasing HHI and decreasing NEC suggest that the overcapacity situation in the polysilicon industry has been being somewhat alleviated through consolidation since 2011, and in 2013, it was an unconcentrated market with fewer but larger producers. With the improved gross margins and net incomes for the major manufacturers in 2014, the polysilicon market has gradually shifted from aggressive pricing strategies for winning market share into a more consolidated market with improved profitability. However, despite the recovering market and upward price trend of polysilicon, today's spot price range of polysilicon may be too low to provide the required rate of return for the manufacturing investors after modeling "all-in" production costs and MSPs for multiple scenarios (technologies, purities, and facility locations). In the bottom-up cost model, the FBR with silane method affords the lowest cash costs; however, compared with the Siemens with hydrochlorination method, a higher CapEx of FBR could translate to a higher "all-in" production cost and a higher MSP, especially given the challenges to secure the upfront capital funds from project financing for building the new manufacturing facilities. Relative to the currently predominant production in urban regions in China, western rural regions in China would provide a "lowest cost" scenario for the country, primarily due to the low electricity and labor rates. Although Chinese manufacturers have a lower regional WACC, which would lead to a lower MSP, highly leveraged capital structure at the corporate and industry level is a warning signal since high corporate debt eventually would increase WACC due to the costs of financial distress. Finally, today's high capital cost requirements in the polysilicon industry present a significant entry barrier. This high barrier to entry could deter new entrants and could also catalyze further consolidation in the polysilicon industry.

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Ran Fu received the B.A. degree in civil engineering from Tongji University, Shanghai, China, in 2008 and the M.S. degree in civil engineering from the University of New Mexico, Albuquerque, NM, USA, in 2014.

He is currently working with the National Renewable Energy Laboratory (NREL) Strategic Energy Analysis Center, Golden, CO, USA, where his analysis activities are focused on solar energy technologies (from the upstream manufacturing to the downstream system installation), energy economics, and policy. Before joining NREL, he was a Project Engineer with three years of experience in the development of commercial and utility-scale solar photovoltaics projects worldwide in the U.S., Canada, Spain, and Chile.

Ted L. James received the B.A. degree in environmental science from Washington University, St. Louis, MO, USA, in 2004 and the M.B.A. degree from the University of Colorado, Boulder, CO, USA, in 2014.

He currently leads the Clean Energy Manufacturing Competitiveness Analysis Group, National Renewable Energy Laboratory (NREL), Golden, CO, USA. Before joining NREL in 2008, he provided consulting services on global business and trade and undertook environmental and energy work across Asia.

Michael Woodhouse received the dual Ph.D. degree in physical chemistry and materials science from Colorado State University, Fort Collins, CO, USA.

For his dissertation, he developed a methodology to rapidly produce combinatorial libraries of novel metal oxide semiconductors using inkjet printing. The material libraries were then screened and optimized to produce hydrogen using water and visible wavelength light. After graduate school, he went to the National Renewable Energy Laboratory (NREL), Golden, CO, where his primary research interests include the development of novel, air-stable materials and architectures for organic-based solar cells. Prior to graduate school, he served for several years as a high school Physics and Chemistry teacher. He is currently a Member of NREL's Strategic Energy Analysis Center, Golden, where his analysis activities are focused on solar energy technologies, economics, and policy. He also serves as an Associate Editor for the American Institute of Physics peer-reviewed *Journal of Renewable and Sustainable Energy* and as the Lead Economics Analyst for the Bay Area Photovoltaics Consortium.